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Evaluation of a Portable Computer with a Wireless Transflective Display for use in Avionics Cockpits*

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ABSTRACT

Display technologies are being developed to enable commercial products like electronic paper, electronic tablets, and wireless information appliances. These products offer an opportunity for evaluation to determine their suitability for use in the cockpit environment and other defense applications. It is important to evaluate the maturity of a new technology alternative, in this case a transflective active matrix liquid crystal display (AMLCD), before considering its use in critical applications. This paper reports the results of an initial evaluation of a portable computer with a light-weight wireless transflective display. The display is characterized in a dark ambient and then again when illuminated with simulated full sunlight in terms of its luminance and contrast ratio. The contrast ratio values are evaluated to determine the optimum viewing angles and conditions. Also, an operator performance study was conducted to assess display legibility.

Keywords: transflective active matrix liquid crystal display, wireless network, VESA, flat panel display metrology, reflection, contrast ratio, luminance, legibility

INTRODUCTION

The transmissive AMLCD is currently the preferred technology for most aircraft cockpit displays. The high ambient illumination forces the displays to have high power backlights to achieve a high contrast ratio for legibility. Increasing the peak luminance and contrast ratio of these panel-mounted units becomes prohibitive due to the high power dissipation and reliability impact. Also, the power, weight, and volume requirements of these high performance displays are too great to permit achieving the same performance in demountable versions that can replace paper checklists and maps with electronic counterparts.

Transflective active matrix liquid crystal display (AMLCD) technology is a lower-power alternative to transmissive, backlit AMLCDs. The displays have been designed to take advantage of sunlight and be used in high ambient illumination conditions.

Architecture. Figure 1 shows the general architecture of a transflective display.

Figure 1. Transflective display structure

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A transflective AMLCD display is almost identical to a conventional AMLCD with the addition of a transmissive reflective (half mirror) layer between the bottom polarizer and the liquid crystal pixel cells. This reflective layer reflects the ambient illumination to increase the effective luminance of the display.

Evaluation Unit. The Panasonic Toughbook 07 is the unit that will be discussed in this report. The unit consists of a CPU "brick" which has a 300 MHz Pentium III processor that connects to a wireless transflective AMLCD module via a radio frequency link. The unit is ruggedized and was designed using MIL-STD-810F test procedures. The unit's wireless transflective display makes it extremely important in terms of metrology techniques and electrical interface.

Display Specifications. The wireless display part of the Toughbook 07 is named Mobile Data Wireless Display (MDWD). The viewable area of the display is 21.5 cm (8.4 in.) diagonal with a 4:3 aspect ratio at 17.1 x 13.0 cm (6.75 x 5.125 in.). The resolution is 800 x 600 with 47 pixels per cm (118 pixels per in.). It will display 256 colors (8 bit). The wireless (IEEE 802.11b) range is specified at 91 m (300 ft.). The backlight has 3 levels: off, low, and high. The power for the MDWD is provided by an 1800 mAH /7.4 V lithium-ion battery pack, allowing the unit to operate for 4 hours with the backlight off, 2 hours with the backlight on low, and for 1.5 hours with the backlight on high.

WIRELESS NETWORK INTERFACE

The Toughbook 07 is one of a new species of wireless information technology that promises to deliver truly mobile computing to consumers in the future. It utilizes a radio frequency communication link as specified in the IEEE 802.11b standard, a.k.a. "Wi-Fi" for wireless fidelity - one of several competing standards for wireless computing. The computer's 802.11b interface handles both the display interface and the computer's local area network interface. In assessing the performance of the wireless link, the issues of standardization, throughput, range, security, and overall utility were chosen to be of primary importance to the aerospace user community.

Current wireless standards, throughput & range. Wireless local area networks (WLANs) permit rapid implementation of networks, networking where cable routing is prohibitive, and increased mobility. Four WLAN standards are of major focus. These standards include IEEE 802.11a, 802.11b, 802.11g (proposed), and Bluetooth.[1] Table I compares the maximum throughput and range of these standards.

Table I. Wireless LAN throughput and range

	Max Thruput Mbps	Range-m	Freq. GHz
IEEE 802.11a	54	18	5.0
IEEE 802.11b	11	91	2.4
IEEE 802.11g	≈ 54	91	2.4
Bluetooth	0.723	10	2.4

The 802.11b standard uses direct sequence spread spectrum (DSSS) modulation and can essentially provide the performance of a 10baseT Ethernet connection while 802.11a uses orthogonal frequency division multiplexing (OFDM) and provides the capability for streaming video and multimedia applications. The new 802.11g standard provides for backward compatibility with 802.11b while using the OFDM modulation defined in 802.11a for higher throughput. Ratification of the 802.11g standard is anticipated to happen in late 2002.[2]

On the other end of the WLAN capability spectrum lies Bluetooth. It is a robust, low complexity, low power, and low cost open-source technology to allow a wide range of devices to communicate with each other. Each unit can communicate with up to seven other units in a short-range ad hoc network.

As a part of our evaluation, a test was designed to evaluate the Toughbook 07 MDWD's 802.11b interface for image update rate, effect of encryption, and communication range. The MDWD and CPU were connected in a simple ad hoc configuration of two wireless nodes. A file consisting of 100 feature-rich color map and graphic images was assembled and loaded into the Toughbook 07 CPU. These images were sequentially displayed on the MDWD using the touch screen stylus to increment each image as rapidly as possible. This was done for ranges from side-by-side to 55 m in an indoor, more controlled, environment. The average image refresh time was 1.3 seconds with encryption disabled and 1.4 seconds with 128-bit encryption enabled. There were no connection problems in line of sight testing to 55 m; however, concrete walls limited the operating distance.

However, in our outdoor tests, the MDWD experienced intermittent connection problems with the CPU at ranges beyond 80 m. Throughput was consistent until the communication link was lost. This difficulty was attributed to potential RF interference in the 2.4 GHz band. The direct-sequence spread spectrum technology provides some immunity to interference.

In addition to 802.11b, some wireless phones and Bluetooth devices share the same portion of the spectrum, possibly creating conditions that may erode the performance of the wireless link especially as these devices become more common in the future. Although Wi-Fi can accommodate up to 11 megabits per second (Mbps), the actual throughput varies with interference and the auto-sensed signal strength and may be reduced to 5.5, 2, or 1 Mbps.[3] As a result, the FCC is considering options to better enable different devices to share the limited spectrum while reducing the chance of interference.[1]

Security. Unfortunately, the encryption capability offered by the 802.11b standard, called "wired equivalent privacy" (WEP), is widely considered to be inadequate for sensitive commercial or military applications, but might be considered sufficient for other uses. WEP features two levels of static key algorithm encryption - 64-bit and 128-bit - which are basically insecure. A recent paper outlines a method for extracting the master WEP key from network traffic and a Linux program boasts the ability to determine the WEP key by passively monitoring between 100 megabytes and 1 gigabyte of network traffic. [4]

Fortunately, the security deficiencies inherent in the 802.11b standard can be rectified with hardware and software solutions developed by third-party vendors, although at some expense to the customer. Furthermore, the IEEE 802.11 Task Group 1 is currently working on enhancing the security of the standard.[5]

Overall utility. Although the display is capable of refreshing feature-rich images fast enough for either the automotive consumer or a pilot using the device as a navigation tool**,** the Toughbook 07 is unable to fluidly display full-motion video. The weak encryption capability may be adequate for motorists to retrieve information in the vicinity of their vehicles, but without augmentation it is unacceptable for the transfer of sensitive personal and military data in the presence of an adversary capable of decrypting the transmission.

DISPLAY EVALUATION

Metrology. Metrology standards have accommodated projection and emissive display technologies. The challenge for reflective technologies is to make a proper quality evaluation.

What makes the metrology of a transflective display different from a standard flat panel display? The ambient illumination is considered a benefit and in most cases is necessary for optimum display performance. The reflectivity of the panel should be compared to a metric such as the reflectivity of white paper or an instrument panel gauge or mechanical flight instrument. Table II is a comparison between white paper and the Toughbook 07 transflective display in an average outdoor diffuse ambient (roughly 27.5 klx).

Table II. Display vs. paper luminance characteristics.

	L cd/m^2	CIE u'	CIE v'
Paper	2973.8	0.193	0.444
Display	733.2	0.195	0.476

The color coordinates indicate the transflective display screen shifts the color slightly toward the yellow on the CIE chromaticity diagram. The display screen is noticeably less reflective than white paper at roughly one fourth the luminance.

Tests Performed. This display evaluation was based on the VESA Flat Panel Display Measurements Standard,[6] the Society of Automotive Engineers (SAE) J1757 Draft Standard Metrology for Vehicular Displays,[7] and MIL-HDBK-87213 Electronically/ Optically Generated Airborne Displays.[8]

The VESA standard describes a suite of basic measurements (SBM), consisting of 16 tests, to characterize the optical performance of a display. The image test patterns are available from the VESA website.[9] However, in the present case it is important to extend the analysis beyond the 16 basic tests to address the transflective issues and how the reflective touch screen affects display legibility.

SAE J1757 describes a procedure for direct sun-light exposure when the reflection angle does not intersect a part of a windshield, side windows, rear window or sunroof of a vehicle. It is assumed this test is valid because direct screen reflections can be avoided since the display is portable.

MIL-HDBK-87213 section 3.2.1.6.3 Multi-Function Display (MFD) Luminance and Contrast is the most severe contrast-ratio measurement test. This test subjects the display to both direct sunlight and diffuse reflected light.

The display screen contrast-ratio is evaluated over a series of viewing angles with a sun lamp (projection source) perpendicular to the screen. This test provides screen diffuser information to determine where the contrast ratio is highest under direct illumination.

VESA Suite of Basic Measurements. All measurements made for this group of tests were performed in a dark ambient with the backlight on high unless otherwise noted.

The SBM starts with measuring the center of the display to determine its contrast ratio. These measurements were made according to VESA section 302, Center Measurements of Full Screen, and are reported in Table III. Table III includes VESA tests 302-1 to 302-3: Luminance and Color of Full-Screen White, Luminance and Color of Full-Screen Black, and Contrast Ratio (C_R) of Full Screen. The average office lighting measurements were made to determine how usable the display was without its backlight turned on.

Table III. Tests 302-1 to 302-3: Full Screen Center Luminance, Color, and Contrast Ratio

Full Screen Center Performance-			
	Luminance` (cd/m^2)	CIE u'	CIE v'
Backlight High Level			
White	40.1	0.209	0.471
Black	4.0	0.200	0.440
C_R	10		
Backlight Low Level			
White	25.7	0.215	0.464
Black	2.5	0.202	0.437
C_R	10		
Average Office Lighting- no Backlight			
White	10.9	0.225	0.520
Black	2.9	0.222	0.511
C_R	3.4		

A typical computer monitor has a luminance of approximately 170 cd/m^2 or greater and a contrast ratio of 80 or greater. The Toughbook 07 display is comfortable to view at roughly one fourth the luminance (backlight on high) under average office lighting (approximately 4.4 klx with color coordinates of (u', v') = (0.224, 0.515). The white display screen luminance under typical office lighting, with the backlight on high, was 51 cd/m^2. This made the contrast ratio approximately 7.5. Also, once again, the CIE 1976 color coordinates indicate a color shift toward the yellow spectrum in ambient room light (Table III).

VESA test 302-4, Gamut and Colors of Full Screen, are listed in Table IV. The measurements show the photopic luminance balance between each primary color and the associated 1976 CIE color coordinates.

Table IV. Test 302-4 Gamut and Colors of Full Screen.

Full Screen Center Performance			
	Luminance (cd/m^2)	CIE u'	CIE v'
Red	13.4	0.281	0.462
Green	21.1	0.195	0.495
Blue	11.8	0.159	0.416

VESA test 302-5, Gray-scale of Full Screen measurement, is readily interpreted graphically in a luminance vs. gray-scale plot as shown in Figure 2. The curve is typical for displays with gray-scales that follow a gamma-type behavior.

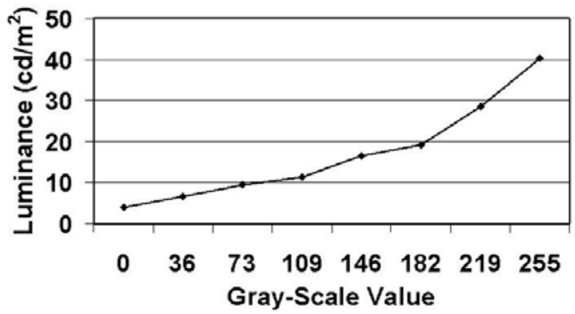

Figure 2. Test 302-5: Eight-Level Gray-Scale of Full Screen.

VESA test 303-4, Shadowing (Gray-Scale Artifacts) measures shadowing caused by different gray-scale patterns on the display. The artifacts must be visible to be measurable. There were no noticeable artifacts.

VESA test 304-9, Checkerboard Luminance and Contrast, uses a checkerboard pattern to measure the screen pattern effect (artifacts) on contrast ratio (C_c). A 5 x 5 checkerboard pattern was chosen for the test. The results are shown in Table V. The contrast is comparable with test 302-3.

Table V. Test 304-9 Checkerboard Luminance and Contrast.

Odd/Odd Checkerboard-Backlight On High	
Checkerboard	5 x 5
Luminance-White Screen (L_w) (cd/m^2)	35.5
Luminance-Black Screen (L_b) (cd/m^2)	3.4
Contrast Ratio-Checkerboard (C_c)	10.3

VESA test 305-1, Response Time, uses a photometer and an oscilloscope to capture the transition from a black to white screen (on-time) and from a white to a

black screen (off-time). The oscilloscope is connected to the photometer's photomultiplier tube amplifier output. The pixel turn-on time was measured to be 2.4 ms. The pixel turn-off time was measured to be 6 ms. If one assumes 24-30 frames per second is required for video, the display performance is adequate.

VESA section 306, Uniformity, is reported in Table VI. The five-point uniformity tests, tests 306-1 to 306-3, involve measuring the luminance of a white (L_w) and black (L_b) screen, color coordinates (u'_w , v'_w), and correlated color temperature (CCT) near the four corners and at the center of the display. The nonuniformities are calculated for L_w, L_b, contrast ratio (C_U) and CCT using the formula:

Nonuniformity=100%(L_{max}-L_{min})/L_{max}. The color difference is calculated using the formula:

$\Delta u'v' = \sqrt{(u_1' - u_2')^2 + (v_1' - v_2')^2}$

Table VI. Tests 306-1 to 306-3, screen luminance, contrast ratio, and CCT nonuniformity and color difference

5 pt	L_w	L_b	C_U	u'_w	v'_w	CCT
1	37.9	4.15	9.1	0.211	0.471	5582
2	39.5	3.98	10.1	0.214	0.467	5583
3	39.9	3.84	10.5	0.209	0.472	5609
4	37.7	3.41	11.1	0.209	0.468	5877
5	38.4	3.45	11.0	0.209	0.478	5368
Ave.	38.7	3.77	10.4	Max		5604
Min.	37.7	3.41	9.1	$\Delta u'v'$		5368
Max.	39.9	4.15	11.1	↓		5877
Nonunif.	5%	18%	18%	0.011		8.7%

VESA test 306-6, Anomalous Nonuniformity, documents irregularities in the uniformity of a white screen. There were no noticeable nonuniformities when a white screen was displayed. This test was not performed.

VESA test 307-1, Four-Point Viewing Angle measurement, was expanded to VESA test 307-2, Threshold-Based Horizontal and Vertical Viewing Angles, to determine a better overall knowledge of the viewing cone of the display. White screen and black screen measurements were made at 5° increments from perpendicular at center screen, first with the screen held normal in the vertical direction and next with the screen held normal in the horizontal direction. The peak contrast ratio was 12.8 with the screen held normal in the vertical direction and the left side of the display toward the spectroradiometer at 10°. The peak contrast ratio was 11 with the screen held normal in the horizontal direction and the top of the display tilted away from the spectroradiometer at 5°.

After finding the peak contrast ratio in both the horizontal and vertical directions, another measurement was made at the peak contrast ratio point on the display. With the left side of the display toward the spectroradiometer at 10° and the top of the display tilted away from the spectroradiometer at 5°, the true peak contrast ratio was found to be 13.4.

The contrast ratio vs. viewing angle of the display is shown in Figure 3. The contrast ratio peak indicates the display is optimized for use by right-handed people and accommodates the majority of the population. It would also work well located on the right side of a vehicle operator in or on the vehicle console. Without measuring contrast values at 5º increments, these characteristics could not have been found.

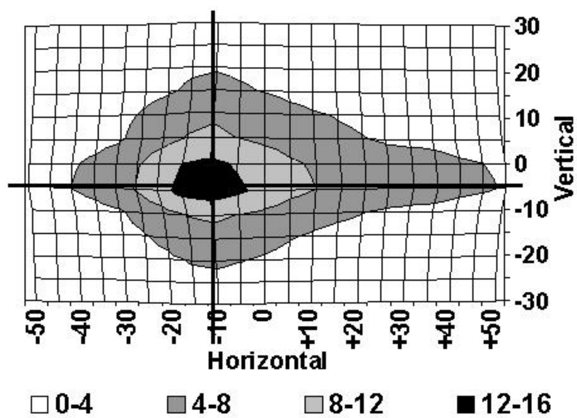

Figure 3. Contrast ratio vs. viewing angle

VESA test 308-2, Ambient Contrast Ratio, requires a large diffuse light source that our laboratory does not have. The ambient contrast ratio is derived in the later SAE J1757 section, the MIL-HDBK-87213 section, and the projection-source only section.

VESA test 401-1, Display Power Consumption, was not directly measured. It was estimated from battery life. The battery capacity is 1800 mAH at 7.4 V. The three battery load conditions are backlight off, low and high with specified times for battery operation of 4, 2, and 1.5 hours respectively. Dividing the battery capacity by the operating hours and then multiplying the result by the battery voltage determines the power consumption of the display. The three levels of operating power are estimated to be 3.3 W, 6.7 W, and 8.9 W. This power includes the wireless interface electronics in the display. The actual display power without backlight is probably closer to 0.3 W. This assumes the computer and wireless interface require approximately 3 W. The low and high backlight mode power consumption

would therefore be closer to 3.7 W and 5.9 W respectively.

VESA test 402-1, Frontal Luminance Efficiency, _, is a combination of VESA tests 401-1 (Power Consumption) and 302-1 (Luminance and Color of Full Screen White). The _ for this display with the backlight on high and low, assuming 3.0 W for the computer and interface, is 6.8 cd/m^2/W and 7.3 cd/m^2/W respectively.

SAE J1757 Vehicular Display Metrology. SAE J1757 describes five methods for contrast ratio measurement:
Method 1: diffuse ambient light measurement, using a Sample Sphere Method (Skylight only illumination simulation)
Method 2A: direct sun-light exposure (Critical Specular Light Cone (CSLC) intersects a part of the windshield, side windows, rear window or sunroof) 45 klx illumination
Method 2A: diffuse sky-light illumination (no direct sun-light) (Critical Specular Light Cone (CSLC) intersects a part of the windshield, side windows, rear window or sunroof) 5 klx illumination
Method 2B: direct sun-light exposure (CSLC does not intersect a part of the windshield, side windows, rear window or sunroof, or the display position in the car is not known) 45 klx illumination
Method 2B: diffuse sky-light exposure (no direct sun-light) (CSLC does not intersect a part of the windshield, side windows, rear window or sunroof, or the display position in the car is not known) 5 klx illumination

The display was initially evaluated in different types of environments. After taking the display outdoors it became very apparent that we were basically looking at a mirror, especially with the touch screen overlay. This immediately made the tests for Methods 2A direct sun-light exposure and diffuse sky-light illumination, where the screen reflections are directly visible, impractical. Under diffuse skylight conditions it was very difficult to avoid glare from the sky and clouds or from the face of the viewer or light colored clothing.

Method 2B. direct sun-light exposure was chosen in the sample test because the display viewing angle is adjustable and direct screen reflections can be avoided.

A 45 klx light source was set at 45° off normal and the IS 320 spectroradiometer was moved in 5° increments from the panel normal (display axis) to the default measuring point of 30°. A white circle was imaged on the center of the screen for the white screen luminance measurements as shown in Figure 4. The same angles were then measured with the screen black. The backlight was not on.

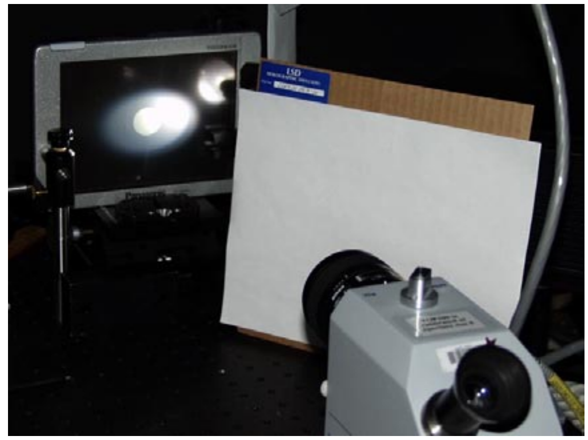

Figure 4. SAE J1757 method 2B setup

The contrast ratio of the screen from normal to 30°, tilted with the left side of the screen toward the spectroradiometer, is shown in Figure 5. The contrast ratio peak was 5.3 at 25°.

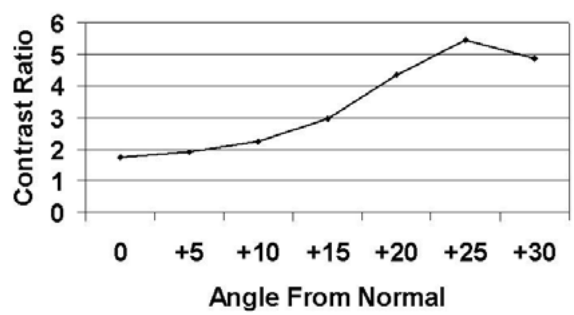

Figure 5. Contrast ratio obtained from Method 2B

The preferred viewing angle of the display for this test was just beside the specular reflection region (+45°) of the illumination source, toward the center of the display (at +25° from normal).

MIL-HDBK-87213 method. A Hoffman LM-33-52 sunlight contrast measurement system is used for this test. The setup consisted of the following: a 107 klx (10 kfc) direct illumination source (projection source) normal to the center of the screen, a diffuse source of 7160 cd/m^2 (2055 fL) at 30° from the right of the screen, and the photometer 30° to the left of the screen. The white screen luminance was 4248 cd/m^2 and the black screen luminance was 1679 cd/m^2, yielding a contrast ratio of 2.5. This value means the display may be usable for simple text or graphics in non-critical applications, but is not suitable for

complex applications (imagery) or critical applications (flight instruments).

Projection-source only. In an attempt to more fully understand the effects of direct illumination, the MIL-HDBK-87213 test was performed without the diffuse light source. Direct illumination of 107 klx only from the projection source perpendicular to the display was measured at 5° increments from 15° to 30°. The contrast ratio curve is shown in Figure 6. The contrast ratio peaks at 5.3 at 25° from normal.

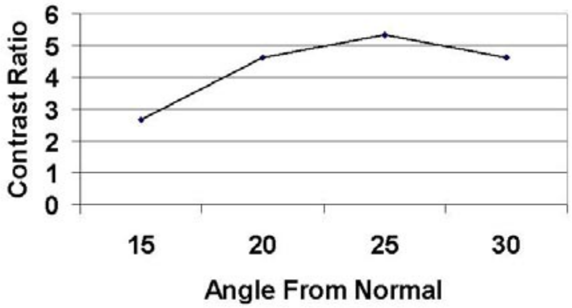

Figure 6. Contrast ratio obtained over a series of viewing angles using projection light source.

Ambient illumination test discussion. Both of the ambient illumination tests show the highest contrast ratio point at 25° from the display screen normal (one with 45° incident illumination (SAE J1757), and one with perpendicular illumination (MIL-HDBK-87213 projection-source only)). This shows that the diffuser in the display is able to spread the incident illumination 25°. The display is apparently designed so that it can receive direct illumination while giving the viewer the maximum contrast ratio at an angle away from the peak screen reflections. Although the contrast ratio of between 5 and 6 is not overly impressive, the display is very legible. However, this peak legibility is constrained to roughly a 5-10° window around the 25° peak contrast ratio angle.

DISPLAY LEGIBILITY ASSESSMENT

Method. A subjective assessment of Toughbook 07 display legibility was conducted, under indoor and outdoor lighting conditions, by AFRL researchers. Indoor legibility with the backlight on high was assessed to be quite satisfactory. Outdoor legibility was assessed to be very poor due to the mirror-like reflectivity of the display. A human factors pilot study was conducted as a further assessment of the Toughbook 7 display indoor legibility.

Subjects. The subjects were two trained observers with 6/6 (20/20) vision either with or without corrective lenses.

Equipment. The Toughbook 07 computer was used to control stimulus presentation on the wireless display. The display backlight was set to high. A portable tape recorder was used to record the observer responses.

Stimuli. The stimuli were Microsoft Powerpoint slides. Each slide contained a series of five digits taken from a table of random numbers. The digits were separated by two spaces and appeared at one of nine locations on the screen: screen center, one of four corners, or center of top, bottom, left or right edge of the screen. The digits were presented in black on a white background. All digits were presented in Times New Roman font in one of nine font sizes: 8, 10, 12, 14, 16, 18, 20, 24, and 28; at a viewing distance of 58.4 cm (23 in) these fonts subtend angles of 7.9, 10, 11.4, 12.2, 13.3, 14, 17.6, 19.8, and 24.4 minutes of arc respectively. Each of the nine font sizes appeared one time at each of the nine screen locations for a total of 81 stimuli.

Procedure. Fluorescent room lighting was set to the level of a typical office environment. For the initial test, the observer was seated in a comfortable chair directly in front of and at a distance of 0.55-0.60 m from the display. The display was approximately 10° below eye level and tilted backward at an equivalent angle, such that the observer’s line of sight was normal to the display center. The observer was initially shown a screen having a series of five digits in each of the nine locations and the task was explained. The observer’s task was to read the five digits from each slide. The slides changed at three-second intervals. After a few practice slides were presented, the observer signaled readiness to begin. The portable tape recorder was then activated to record the observer’s responses, and the series of 81 test stimuli were presented. This procedure was repeated with the display to the right of the observer such that the observer’s viewing angle to the center of the display was 30°.

Results. For each of the viewing conditions, percent errors was calculated for each font size at each screen location. The results are shown graphically in Figures 9 and 10. The screen locations are numbered from top to bottom and left to right; i.e., the upper left corner is position number 1, lower left is position number 3, center screen is position number 5, upper right is position number 7 and lower right is position number 9.

Discussion. With the display directly in front of the observer, error rate was very low (Figure 9), only ten percent errors for font sizes 8 and 10 and no errors

for larger font sizes. With the display positioned at a 30° offset to the observer, as might be the case in a vehicle, the error rates were somewhat higher (Figure 10), particularly when the characters were at positions 4, 5, and 6 (vertical centerline of display) and positions 7, 8, and 9 (edge of display farthest from the observer.)

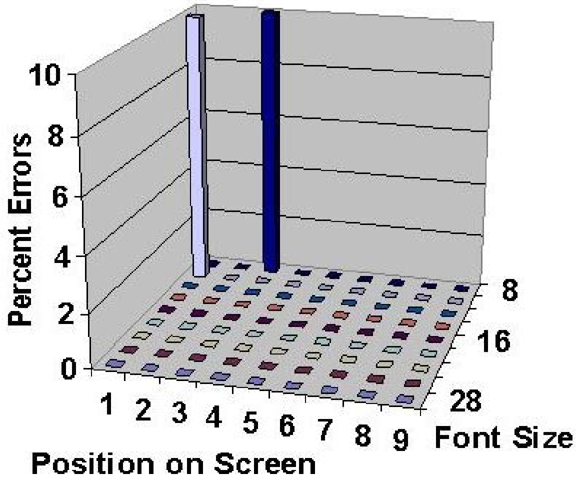

Figure 9. Character reading errors as a function of font size and position on screen; display directly in front of observer.

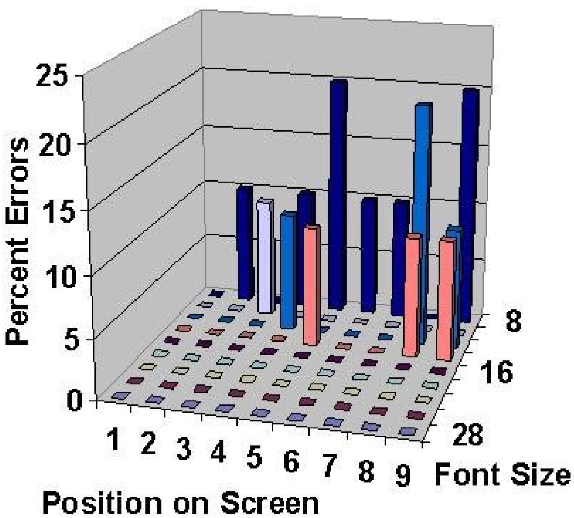

Figure 10. Character reading errors as a function of font size and position on screen; display 30° to the right of observer.

SUMMARY

The Toughbook 07 integrates advanced technologies in order to provide a powerful computing resource for mobile applications. The integration of the stylus operated touch screen interface eliminates the need for an external keyboard thereby greatly increasing reliability; however, it is a serious compromise to the display's optical characteristics. The touch screen surface must be durable and cleanable and, as a result, is more reflective than optically desirable.

The unit is minimally suitable for use in open canopy cockpits, especially under full sunlight illumination. This limitation is primarily due to restricted positioning for optimum display operation. However, in transport cockpits, the unit has greater potential because they are similar to an office environment with windows.

The Toughbook 07 with its wireless link, low power, and low weight display offers interesting potential for in-vehicle applications. The ability to use the display while operating a vehicle and then remove it for remote information access or vehicle setup and control provides added utility and capability.

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